NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4028

PRELIMINARY INVESTIGATION OF PROPANE COMBUSTION IN A 3-INCH-DIAMETER DUCT AT INLET-AIR TEMPERATURES OF 1400° TO 1600° F

By Erwin A. Lezberg

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Cleveland, Ohio

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PRELIMINARY INVESTIGATION OF PROPANE COMBUSTION IN A 3-INCH-DIAMETER DUCT AT INLET-AIR TEMPERATURES OF 1400° TO 1600° F

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SUMMARY

Ignition delays and combustion efficiencies were determined for propane injected into a heated airstream. Spontaneous-ignition delays of 0.007 to 0.049 second occurred with a single-tube injector at temperatures between 1395° and 1585° F. These results followed the Arrhenius relation with an apparent activation energy of 43 kilocalories per mole.

Two types of flames were observed for multipoint fuel injectors: a diffusion flame that stabilized at the injector orifices, and an ignition-stabilized flame that formed a flame front downstream of the fuel injector. Combustion efficiencies for the diffusion flames increased with increasing fuel-air ratio to values of 90 to 100 percent at a fuel-air ratio of about 0.01, with burner lengths 6 inches or longer. Efficiency decreased markedly at burner lengths below 6 inches. Decreasing pressure had only a small effect on the efficiencies. Air temperature had no effect in the range investigated. Combustion efficiencies for the ignition-stabilized flames were below 70 to 80 percent for burner lengths of 18 inches or less and were strongly dependent on burner length and temperature. Efficiency decreased as burner pressure was lowered.

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INTRODUCTION

Air-breathing engines operating at hypersonic Mach numbers will have combustor stagnation temperatures and fuel residence times that are high enough for spontaneous ignition of the fuel. At temperatures above the ignition temperature, efficient combustion might be maintained by continuous self-ignition of the fuel with no flameholder recirculation zone.

Except for some ignition studies (e.g., ref. 1) little experimental work has been done with steady-state combustion at inlet temperatures above 1400° F. The present investigation was initiated at the NACA Lewis laboratory to determine the influence of several inlet parameters on the combustion efficiency of gaseous fuels at air temperatures of 1400° to 1600° F.

Ignition temperatures and delays were determined for gaseous propane injected from a single-point fuel injector into a heated airstream. In addition, multipoint fuel injectors were used to study the combustion efficiency of propane as a function of fuel-air ratio, temperature, pressure, and burner length. Two types of flames were studied with the multipoint fuel injectors: a diffusion flame that stabilized at the injector orifices and a flame that stabilized by spontaneous ignition some distance downstream of the fuel injector.

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Ignition delay and the combustion efficiency of both types of flame were determined for the following conditions:

	Ignition delay	Combustion efficiency
Burner length, in.	11 to 25	3 to 18
Air temperature, °F	1395 to 1585	1448 to 1623
Fuel-air ratio	------------	0.0053 to 0.0176
Fuel-flow rate, lb/hr	4	---------------
Pressure, in. Hg	29	17 to 32
Air velocity, ft/sec	42 to 131	≈115

APPARATUS

Figure 1 shows a schematic diagram of the apparatus. The air supply and exhaust were connected with the laboratory systems. Airflow and exhaust pressure were regulated by remote-control valves. The air was heated in an electric resistance heater consisting of three 5/8-inch-diameter Inconel tubes in an insulated box.

The test section consisted of a 6-foot-long insulated tube of 3-inch inside diameter, fabricated from 1/8-inch-thick Inconel. Two windows were provided for observation of the flames. A movable, air-atomized water spray, shown at the bottom of the test section, was used to quench the reaction and to vary the combustor length, which is defined as the distance from the fuel injector to the quench spray.

Commercial propane (97.8%) was taken from a cylinder and was passed through a fuel injector suspended from the top of the test section. The fuel injectors are shown in figure 2. The injector used for the spontaneous-ignition study consisted of a coiled tube with 0.08-inch inside diameter, immersed in the hot airstream. The multipoint injectors (concentric-ring and spoke types) used for the rest of the program were designed to give an approximate-step concentration profile: a fairly flat concentration at the core and low fuel concentrations at the wall; these injectors were positioned about 9 diameters downstream of the air inlet.

Inlet-air temperatures were measured by a Chromel-Alumel thermocouple and were corrected for radiation losses with a wall temperature measurement at the same axial position. Fuel temperatures were determined with Chromel-Alumel thermocouples positioned as shown in figure 2. Exhaust temperatures obtained from a six-couple rake located 6 feet downstream from the vertical section were averaged and recorded on a strip chart.

Test-section static pressure was taken at a static tap about 5 inches upstream of the fuel injector. Air, fuel, and quench water were metered through calibrated rotameters.

PROCEDURE

Ignition-Delay Measurements

Combustor length and air velocity were pre-set, and the ignition delay τ was measured as

$$\tau = \frac{l}{U} \tag{1}$$

where l is the distance between the fuel injector and water quench spray, and U is the mean velocity of the airstream at the minimum temperature for ignition.

With the heater on, the air temperature was allowed to rise continuously. The fuel throttle valve was pre-set, and burner pressure was adjusted to atmospheric pressure. For each ignition run, the fuel shutoff valve was opened briefly, and ignition was noted by a sharp rise in the exhaust temperature. Near ignition temperature, data were recorded at 5° to 15° F temperature intervals. The ignition temperature was taken as the average of the closest ignition and nonignition points.

Efficiency Measurements

The fuel flow was adjusted to the desired flow after ignition had been established. The quench-water rate was adjusted to give exhaust temperatures of 900° to 1200° F. Average exhaust temperatures were continuously recorded, and data were taken when approximately steady-state conditions were reached.

All atmospheric runs were made with the maximum airflow. Runs at reduced pressures were made at constant velocity and lowered air mass flows. A fuel-air ratio of 0.0175 was not exceeded, because the temperature of the burner wall became excessive.

Method of Computing Combustion Efficiency

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Combustion efficiencies were calculated from a heat balance. Combustion efficiency η_B is defined as

$$\eta_B = \frac{\text{Actual enthalpy increase}}{\text{Ideal enthalpy increase}}$$

where the actual increase in enthalpy ΔH_{ac} is given as

$$\Delta H_{ac} = (H_{T_2} - H_{T_1})_a + (H_{T_2} - H_{T_1})_f + (H_{T_2}^{\cdot} - H_{T_1})_w + Q_{q,a} + Q_L$$

where the enthalpy changes refer to air a, fuel f, and quench water w from the initial temperature T_1 to the exhaust temperature T_2, $Q_{q,a}$ is the enthalpy change of the quench atomizing air, and Q_L is the heat loss from the duct. Since Q_L amounted to only 3 to 7 percent of the ideal enthalpy rise and required an involved and approximate calculation for each point, its value was not included in the efficiency calculations. The ideal enthalpy rise is the heat of combustion of the fuel at the exhaust temperature.

RESULTS

Ignition Delays and Temperatures

The ignition-temperature-delay measurements are shown in figure 3. The data were taken for combustor lengths of 11 to 25 inches and air velocities of 42 to 131 feet per second. Ignition temperatures were independent of the values of combustor length and air velocity when delay was calculated according to equation (1).

Fuel-flow rate for the single-point injector was held constant at about 4 pounds per hour, which resulted in higher fuel-air ratios for the low-velocity runs. Check runs at lower fuel flows showed no variation in ignition temperature and indicated no significant effect of fuel-air ratio in the very lean range. For comparison, four ignition points are shown for the spoke injectors at 1-atmosphere pressure. Ignition temperatures for the concentric-ring injector were about 100° F lower and were always accompanied by diffusion flames.

Flame Observations

Table I indicates some observations of the flame. Time exposures of the diffusion flame for fuel injector C, which was a spoke injector, are shown in figure 4. Progressive blowoff from the orifices can be observed as the fuel flow is increased, until the flame stabilizes at the central orifice only.

At air temperatures above the ignition temperature, where the flame did not stabilize at the injector, the fuel burned in the duct at some distance downstream from the injector and, in most cases, below the lower window. The type of flame observed when stabilization occurred near the lower window probably was not representative, since the flame tended to stabilize in the recirculation region of the window cavity.

Efficiency of Injector-Stabilized Flames

Table I gives the combustion efficiency data. Figure 5 shows the effect of fuel-air ratio on combustion efficiency for the injector-stabilized diffusion flames. The efficiencies increased to values of 90 to 100 percent at a fuel-air ratio of about 0.01. Fuel flows were limited by blowoff from the injector or by excessive wall temperatures (figs. 5(a) and (b)). A variation in air temperature from 1448° to 1623° F had no significant effect on the efficiencies.

Figures 5(a) and (b) show no appreciable effect of combustor length on efficiency for lengths of 6 inches and longer. Figure 6 shows the decrease in efficiency for injector C at lengths of less than 6 inches. Flame was not stabilized at several orifices at this fuel flow.

The effect of pressure on the efficiency of the injector-stabilized flames is shown in figure 7 at a velocity of approximately 115 feet per second and a fuel-air ratio of 0.013. Efficiency decreased only slightly with decreasing pressure. Flames did not stabilize at static pressures lower than approximately 17 inches of mercury at the temperatures available.

Efficiency of Ignition-Stabilized Flames

Figure 8 shows the effect of air temperature on combustion efficiency for lengths of 12 and 18 inches. The dashed portion of the curve intersects the axis at the ignition temperature. Fuel-air ratio, in the range investigated, did not show an appreciable effect on the efficiencies. However, increasing the fuel flow provided additional cooling of the airstream surrounding the fuel lead-in tube and resulted in lowered efficiencies at constant heater outlet temperature.

The effect of pressure on combustion efficiency of the ignition-stabilized flames is shown in figure 9. Since air temperature varied during these runs, the results are plotted as efficiency drop, compared with the data at 1 atmosphere for the same air temperature (fig. 8).

DISCUSSION

The data of figure 3 are replotted as log ignition delay against the reciprocal of absolute temperature in figure 10. The data follow the Arrhenius relation with an apparent activation energy of 43 kilocalories per mole. The ignition delays and activation energy compare favorably with those found by Mullins for prevaporized kerosene (ref. 2).

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The apparent anomaly of the lower ignition temperatures for the concentric-ring injector was investigated by means of high-speed photography. Ignition was initiated at several centers in the immediate wake of the injector. Residence time in the fuel injector was long enough for considerable cracking of the fuel and resulted in carbon formation. Ignition, in this case, may be more representative of a highly cracked mixture and thus may be associated with lower ignition temperatures.

Combustion of Injector-Stabilized Flames

The mixing process must precede the burning for the diffusion flames. Since the flames may be assumed to burn at near stoichiometric composition, the reaction rates are high and the mixing process will be rate-controlling.

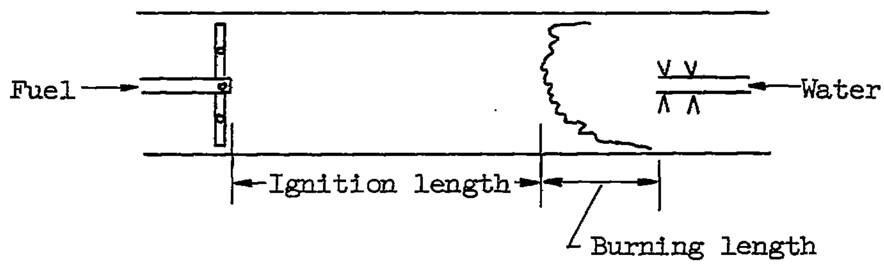
The drop in efficiency at lengths of less than 6 inches (fig. 6) cannot be attributed entirely to quenching of the diffusion flame since, for this particular fuel flow, the flame was not stabilized at all the orifices. Fuel from the nonburning jets could pass unreacted through the quench if flame did not spread from the burning jets. The spreading rate of the burning jet, measured from the included angle of the flame jet photographs, was 20°, compared with about 12° for burning free jets in references 3 and 4.

That fact that combustion efficiency is relatively independent of pressure may be expected from the independence of the turbulence diffusion coefficient on static pressure.

Blowoff from the fuel injectors was not investigated quantitatively. However, the photographs of figure 4 show that blowoff was progressive. Flame held at higher velocities on the center orifice, probably because of the higher blockage of the fuel lead-in tube. Flame blowoff appeared sensitive to configuration and was not complete for the air-cooled injector (D), which operated up to sonic fuel velocity, or for injector C (0.033-in.-diam. orifices).

Combustion of Ignition-Stabilized Flames

At temperatures or fuel residence times greater than those corresponding to the ignition temperature, distance for burning becomes available between the flame front and the quench. The following sketch illustrates the case where the flame does not stabilize at the injector:



Since the over-all mixture is very lean, the combustion rate should be low, resulting in a fairly long time requirement for efficient combustion, in addition to the ignition delay.

SUMMARY OF RESULTS

The following results were observed when gaseous propane was injected into an airstream heated from 1395° to 1623° F.

1. Spontaneous-ignition delays of 0.007 to 0.049 second occurred for propane injected into the airstream from a single tube. The ignition delay data follow the Arrhenius relation, with an apparent activation energy of 43 kilocalories per mole.

2. Two types of flames were observed when injectors with multipoint orifices were used: (1) diffusion flames that stabilized at the injector orifices when conditions for ignition were favorable in the wake of the injector and when fuel flows were low, and (2) ignition-stabilized flames that formed in the duct some distance downstream of the injector.

3: Combustion efficiency of the diffusion flames increased rapidly with increasing fuel-air ratio to values of 90 to 100 percent at a fuel-air ratio of about 0.01.

4. Air temperature and length had no noticeable effect on the efficiency at burner lengths of 6 inches or more. Combustion efficiency decreased markedly at lengths of less than 6 inches.

5. Decreasing the burner pressure to approximately 17 inches of mercury lowered the combustion efficiency of the diffusion flames only slightly.

6. Combustion efficiency of the ignition-stabilized flames was strongly dependent on temperature and increased rapidly at temperatures higher than those required for ignition.

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7. Decreasing the burner length lowered these efficiencies.

8. As pressure was lowered, efficiency of the ignition-stabilized flames decreased.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 14, 1957

REFERENCES

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3. Hawthorne, W. R., Weddell, D. S., and Hottel, H. C.: Mixing and Combustion in Turbulent Gas Jets. Third Symposium on Combustion and Flame and Explosion Phenomena, The Williams & Wilkins Co. (Baltimore), 1949, pp. 266-288.

4. Yagi, Sakae, and Saji, Kenjiro: Problems of Turbulent Diffusion and Flame Jet. Fourth Symposium (International) on Combustion, The Williams & Wilkins Co. (Baltimore), 1953, pp. 771-781.

TABLE I. - SUMMARY OF DATA

Fuel injector	Quench setting, in.	Air flow, lb/hr	Fuel flow, lb/hr	Air temperature, °F	Fuel temperature, °F	Burner static pressure, in. Hg	Air velocity, fps	Combustion efficiency, %	Flame observations
A	9	405	2.48	1533	1463	29.3±0.2	117	10.3	Stabilized at injector
		403	3.46	1526	1457	29.3	116	61.3	
		403	4.25	1516	1452		116	95.3	
		404	4.80	1507	1451		115	103.2	
		405	5.18	1506	1450		116	102.6	Partial blowoff
		404	6.06	1518	1450	(Unsteady)	116	100.3	Intermittent flashing after blowoff
	12	392	2.42	1552	1471	29.2±0.3	114	55.7	
		387	3.46	1539	1466	29.2	112	68.7	
		393	4.26	1527	1465		114	88.5	
		393	5.24	1538	1470		114	-----	Blowoff
		388	2.05	1564	[a]1592		114	63.5	
		391	3.41	1556	1475		114	80.5	
		383	4.16	1536	1475		111	93.4	
		381	4.96	1540	1480		111	96.4	
	18	409	2.19	1473	1413	29.3±0.2	115	53.3	Flame stabilization at injector[b]
		408	2.91	1464	1412	29.3	114	65.5	
		408	3.32	1457	1410		113	92.5	
		410	4.16	1449			114	96.0	
		409	5.07	1448			113	95.4	
		407	5.34	1460	1420		113	87.1	Partial blowoff
			6.22	1455	1415	30.3	109	99.2	"Lifted" flame
			7.18	1471	1425	30.5	109	81.7	Blowoff, partially stabilized at lower window
D	12	389	2.24	1566	1242	28.9	116	15.6	Invisible
		389	3.26	1566	1150	(Unsteady)	116	16.2	
		406	2.32	1579	1250	28.9	122	24.4	
		390	2.40	1578	1245		117	33.7	
		394	3.09	1576	1175		119	27.9	
		392	2.27	1586	1258		118	48.0	
		387	2.48	1587	1245		116	60.6	
		391	3.15	1586	1180		118	44.2	
		391	4.06	1589	1125		118	34.8	
		389	6.05	1576	970		117	89.5	Stabilized at injector
			6.52	1569	944		116	98.5	
			5.46	1566	1016			97.7	
			4.52	1573	1082			102.7	
			4.02	1580	1125		117	90.1	
			3.48	1591	1170	(Unsteady)	117	93.1	
		386	2.86	1593	1220	28.9	116	96.3	
		394	2.23	1604	1280		118	95.5	
		389	2.21	1623	1282		119	69.4	Invisible[c]
	18	391	2.32	1526	1215	28.9±0.3	114	3.5	Invisible
			2.66	1529	1187	28.9±0.3		18.6	
			3.33	1527	1130	(Unsteady)		14.1	
		390	3.81	1527	1087	28.9		20.3	
		391	4.70	1526	1020			19.4	
			4.20	1537	1065		115	38.0	
			4.19	1545	1070	28.9	115	37.2	
			5.21	1549	1000	(Unsteady)	116	36.5	
			6.14	----	----	29.0±2	---	-----	Flashing at lower window
		390	4.20	1557	1080	28.9±0.3	116	48.6	Invisible
		390	4.18	1564	1087	28.9±0.3	116	53.6	Invisible
		389	6.37	1551	935	30.7	115	93.7	Slight flashing, partially stabilized at lower window
		395	4.23	1571	1080	30.8±0.5	111	60.0	Slight flashing visible at lower window
		356	4.23	1560	1058	27.5±1.0	110	47.2	Slight flashing visible at lower window
		315	3.45	1560	1107	24.7	118	43.1	Invisible
		276	3.11	1547	1115	21.9	118	28.6	
		198	----	----	----	15.3	---	No burning	
		388	4.09	1607	1117	28.8	114	71.0	

[a]High fuel temperature probably due to burning around tube at thermocouple position.
[b]Flame was not stabilized at all orifices during any fuel flow.
[c]Fuel did not reignite and stabilize at injector following brief fuel shutoff.

TABLE I. - Concluded. SUMMARY OF DATA

Fuel-injector	Quench setting, in.	Air flow, lb/hr	Fuel flow, lb/hr	Air temperature, °F	Fuel temperature, °F	Burner static pressure, in. Hg	Air velocity, fps	Water flow / Airflow, lb/lb	Combustion efficiency, %	Flame observations
B	12	422	4.15	1514	1267	29.3±0.2	121		70.4	Stabilized at center orifice
		421	3.08	1539	1340	29.3	122		8.2	Invisible[a]
			2.30	1552	1385	29.3±0.4	123		23.5	
			2.85	1549	1354	29.3	122		26.0	
			3.61	1545	1315	29.3±0.5	122		22.4	
		419	2.39	1557	1412	29.3	123		44.0	Stabilized at all orifices
		421	3.13	1550	1362		123		84.2	Stabilized at center orifice - "lifted" flame visible from others
		419	3.67	1544	1330		122		100.1	
			4.02	1540	1314		122		94.3	Center orifice only
			4.73	1534	1275		121		91.0	
		421	5.48	1529	1235		121		94.3	
			5.78	1535	1215		122		91.8	
			6.11	1557	1195		123		92.8	
		391	5.22	1534	1221	29.4±0.5	113		18.3	Invisible
		391	5.10	1533	1245	29.4	113		87.5	Stabilized at center orifice - flame slightly "lifted"
		334	4.56	1515	1257	26.5	106		80.6	
		300	3.96	1520	1282	23.0	110		84.4	
		292	3.77	1550	1324	22.5	115		73.4	
		280	3.64	1558	1330	21.1	114		83.1	
		268	3.51	1566	1350	20.1	115		82.2	
		266	3.03	1584	1380	17.4	133		82.0	
		404	5.25	1562	1250	29.3	118		33.6	Invisible
		404	4.73	1566	1288	29.3	118		65.8	Stabilized at center orifice - "lifted"
		358	4.42	1557	1287	26.1	117		66.1	Stabilized at center orifice - blowoff
		200	2.64	1524	1315	14.0	120		7.2	Invisible
		398	4.66	1625	1344	29.1	121		64.4	Stabilized at center orifice - "lifted"
		405	4.57	1637	1346	21.2	138		53.7	Invisible
	18	397	2.28	1544	1392	29.5	115		45.5	Invisible
			3.28	1539	1332		114		32.1	
			4.10	1533	1274				29.8	
			5.03	1535	1228	29.5±0.5			21.3	
			5.85	1532	1188	29.5±0.7			24.0	
		402	2.38	1558	1414	29.5	117		63.1	Stabilized at center orifice - "lifted" flames at others
		380	2.88	1546	1375		110		78.0	Center orifice only
		384	3.43	1541	1346		111		93.5	
		385	4.01	1535	1314		111		90.0	
		384	4.59	1525	1287		110		92.0	
		384	5.07	1528	1270		110		88.3	
		384	5.65	1530	1240		110		87.5	Stabilized at center orifice
		383	6.24	1553	1215	29.5±0.7	111		71.9	Blowoff
		383	----	----	----	----	---		----	Blowoff
		382	5.46	1568	1260	29.5	112		76.7	Blowoff
		347	4.61	1562	1343	26.3	113		61.0	Stabilized
		311	3.67	1560	1351	23.5	113		78.9	Stabilized
		272	3.24	1554	1355	19.8	118		54.8	Blowoff
		296	3.00	1595	1407	21.1	122		56.0	Stabilized
C	7	398	4.53	1526	1200	29.5±0.4	114	0.248	94.8	Stabilized at injector - some flames "lifted"
	6		4.52	1532	1202	29.5	114	.246	84.5	Stabilized at injector - some flames "lifted"[b]
	5		4.45	1537			115	.243	80.8	
	4		4.45	1540					66.9	
	3		4.52	1541	1198				51.3	
	3		4.44	1549	1205			.215	44.5	
	3		4.46	1551	1209			.194	45.6	
	3	396	4.41	1555	1217			.164	48.6	
	4	397	4.41	1560	1217		116	.188	65.1	
	5		4.35	1564	1230			.186	74.0	
	6		4.30	1568	1235			.185	84.4	
			4.27	1573	1247			.213	92.9	Stabilized at injector - some flames "lifted"
			4.28	1584	1250		117	.230	87.5	Stabilized at injector - some flames "lifted"
		396	2.12	1610	1395		118	.162	66.4	Stabilized at all orifices
		397	2.62	1613	1375		119	.162	67.9	Stabilized at all orifices
		397	3.27	1608	1340		118	.202	88.7	Flame from all orifices - "lifted" flames at 1 to 2 orifices
		396	4.02	1608	1300		118	.235	93.8	
			4.86	1602	1246		117	.255	89.9	Blowoff from several orifices[b]
			5.90	1603	1193		117	.305	94.6	Stabilized at center orifice only[b]

[a]Flame would not restabilize at injector after fuel shutdown.

[b]Evidence of weak burning downstream of quench.

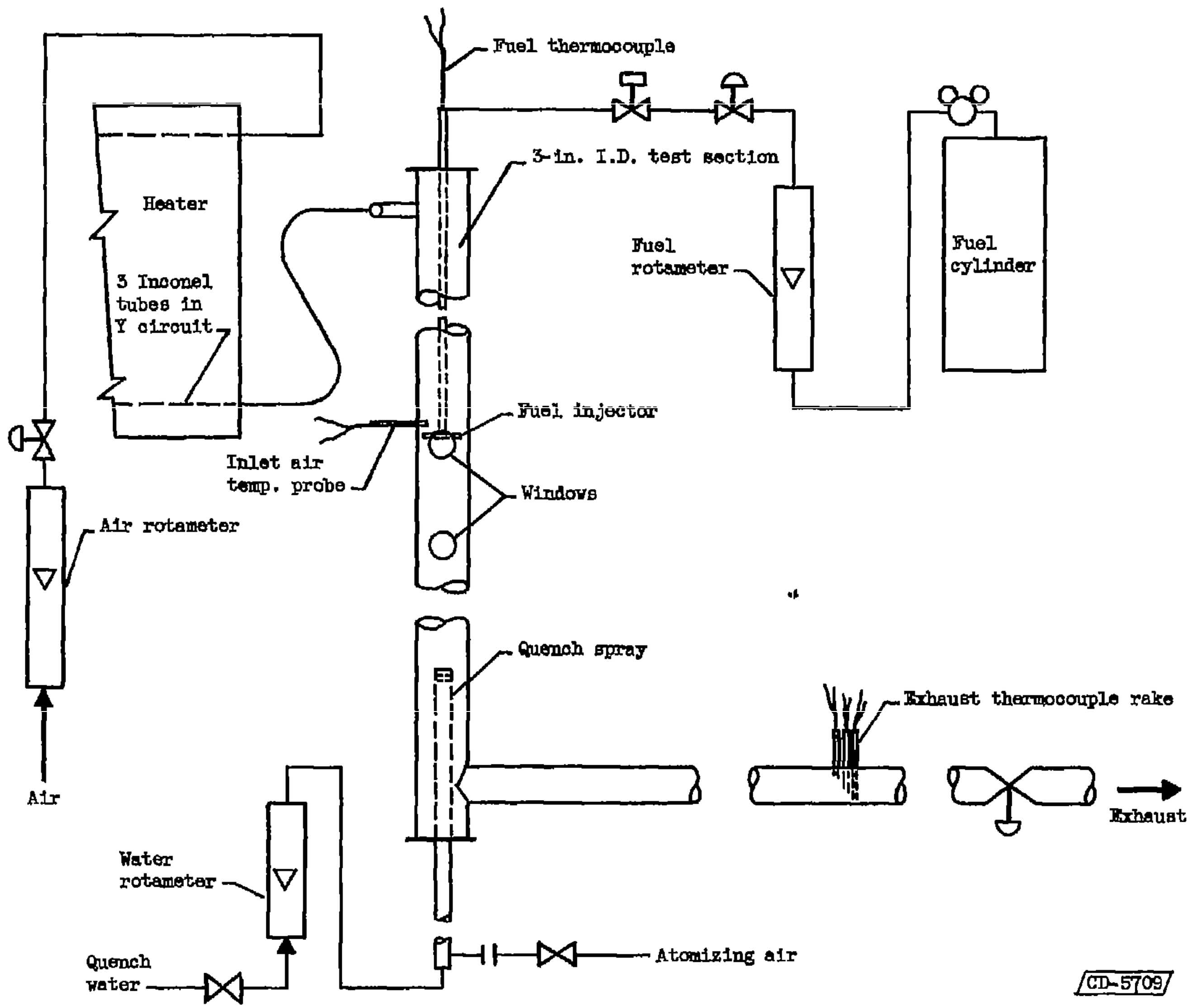
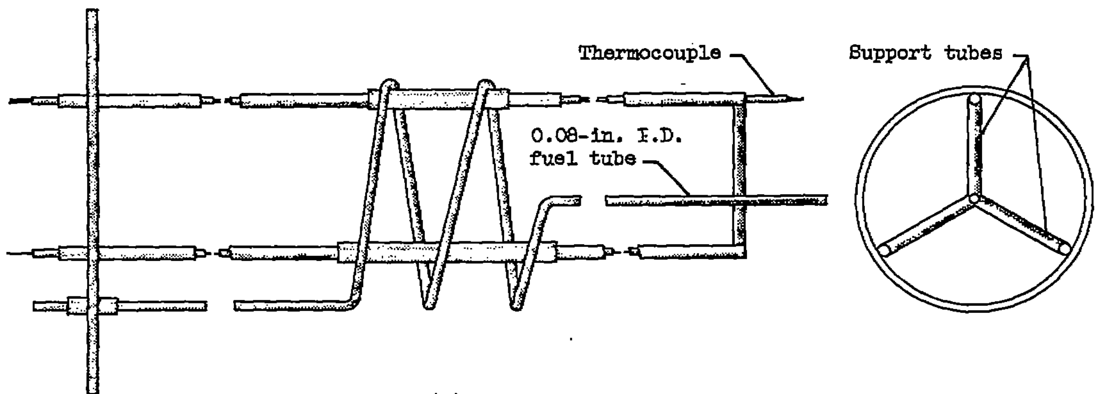
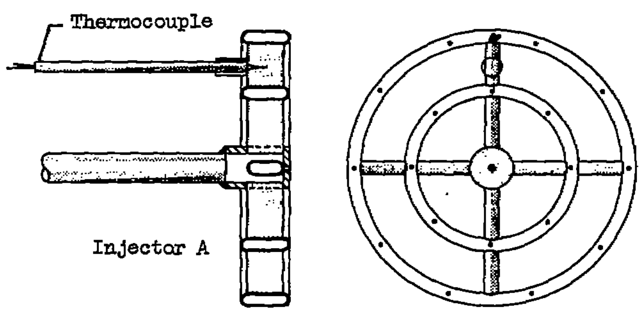


Figure 1. - Schematic diagram of 3-inch-diameter high-temperature burner.

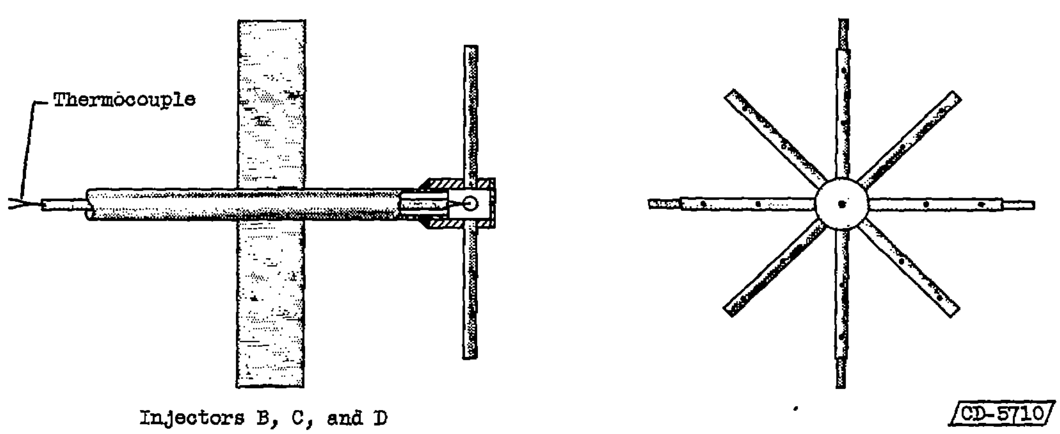


(a) Single-tube injector.



Injector	Diameter, in.	
	Center orifice	Ring or spoke orifices
A	0.028	0.020
B	.028	.020
C	.033	.033
D (air-cooled)	.028	.020

(b) Concentric-ring injector.



(c) Spoke injectors.

Figure 2. - Propane fuel injectors.

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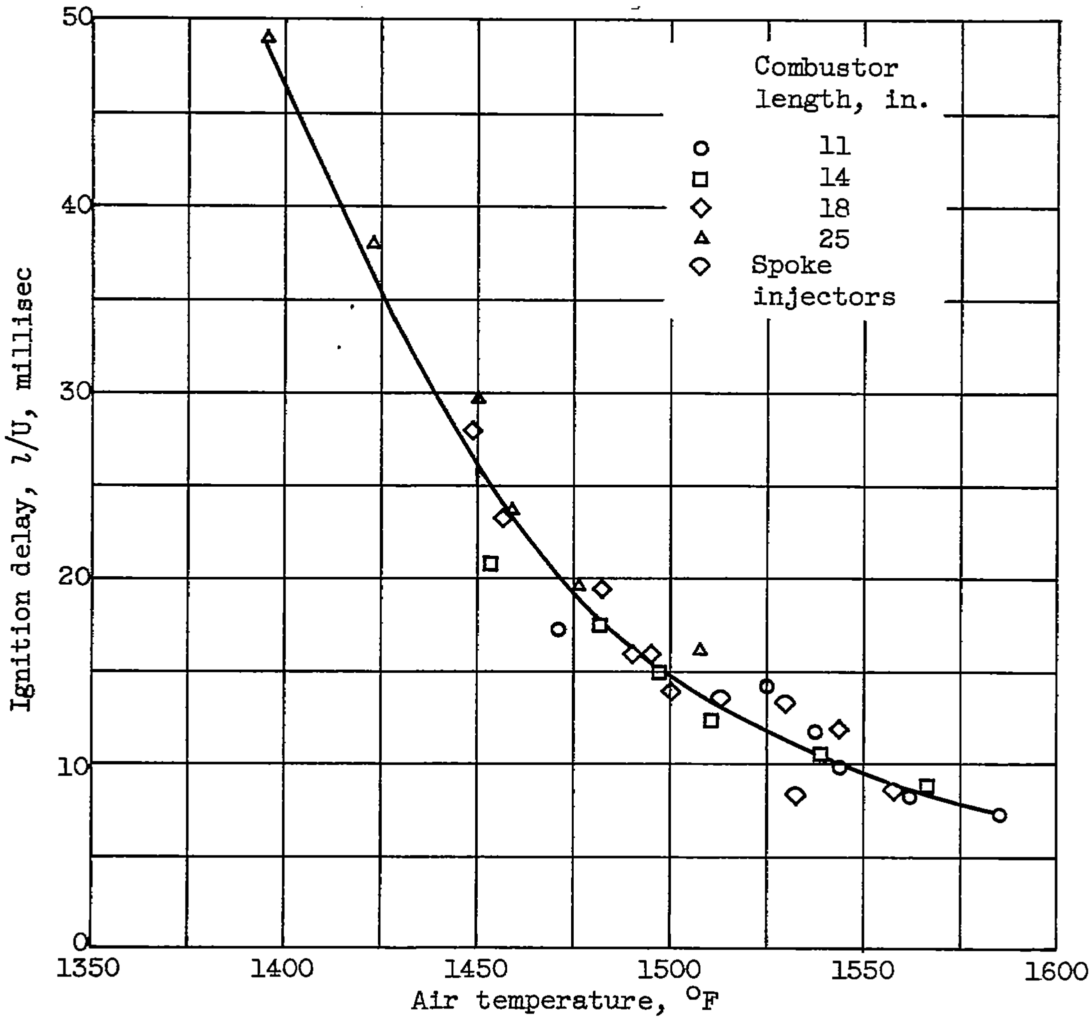

Figure 3. - Spontaneous-ignition delays of propane-air mixtures. Pressure, 1 atmosphere.

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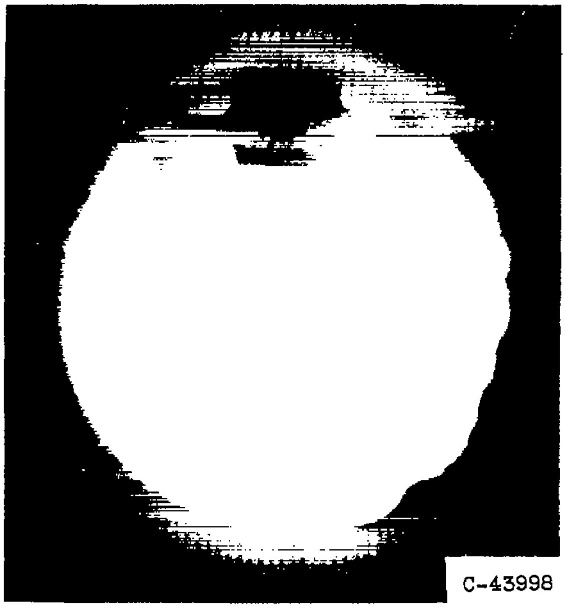
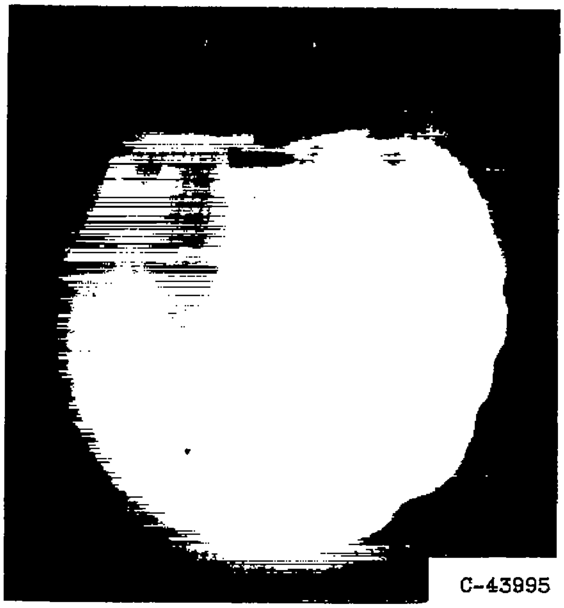
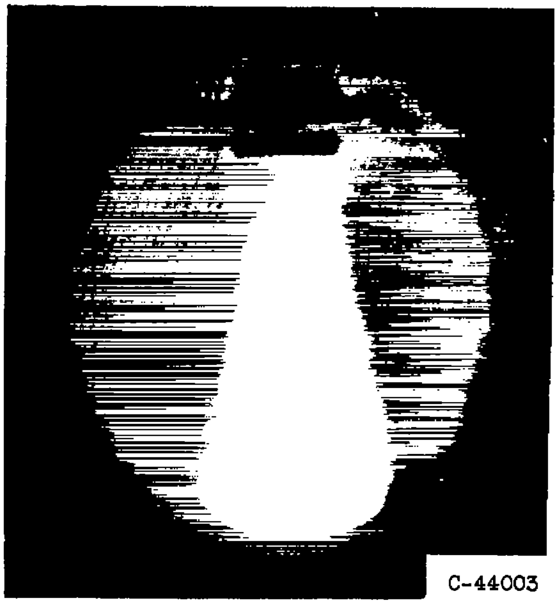


Flame stabilized at all orifices; fuel-flow rate, 3.44 lb/hr



Blowoff from several orifices; fuel-flow rate, 4.11 lb/hr

Blowoff from several orifices; fuel-flow rate, 5.35 lb/hr



Flame stabilized at center orifice only; fuel-flow rate, 6.75 lb/hr

Figure 4. - Propane diffusion flames, injector C. Pressure, 1 atmosphere; air velocity, 115 feet per second; air temperature, 1500° F.

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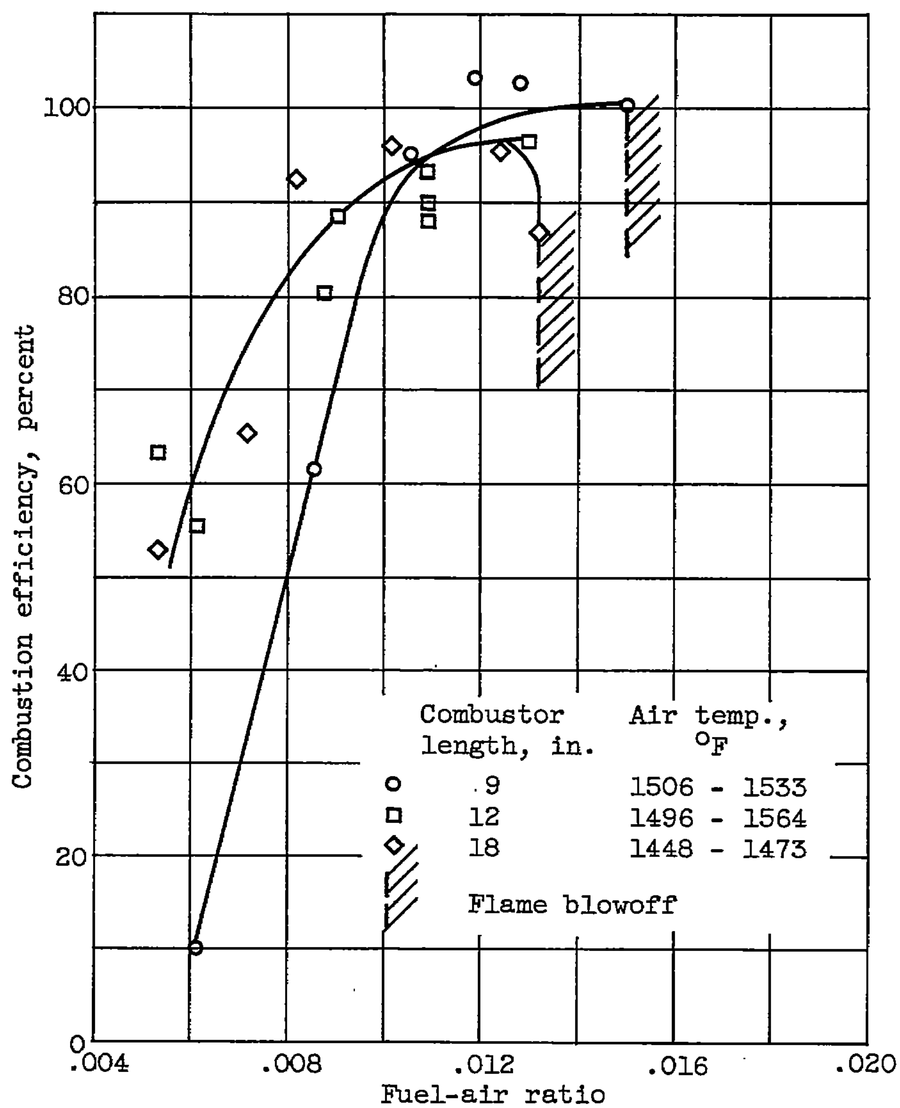
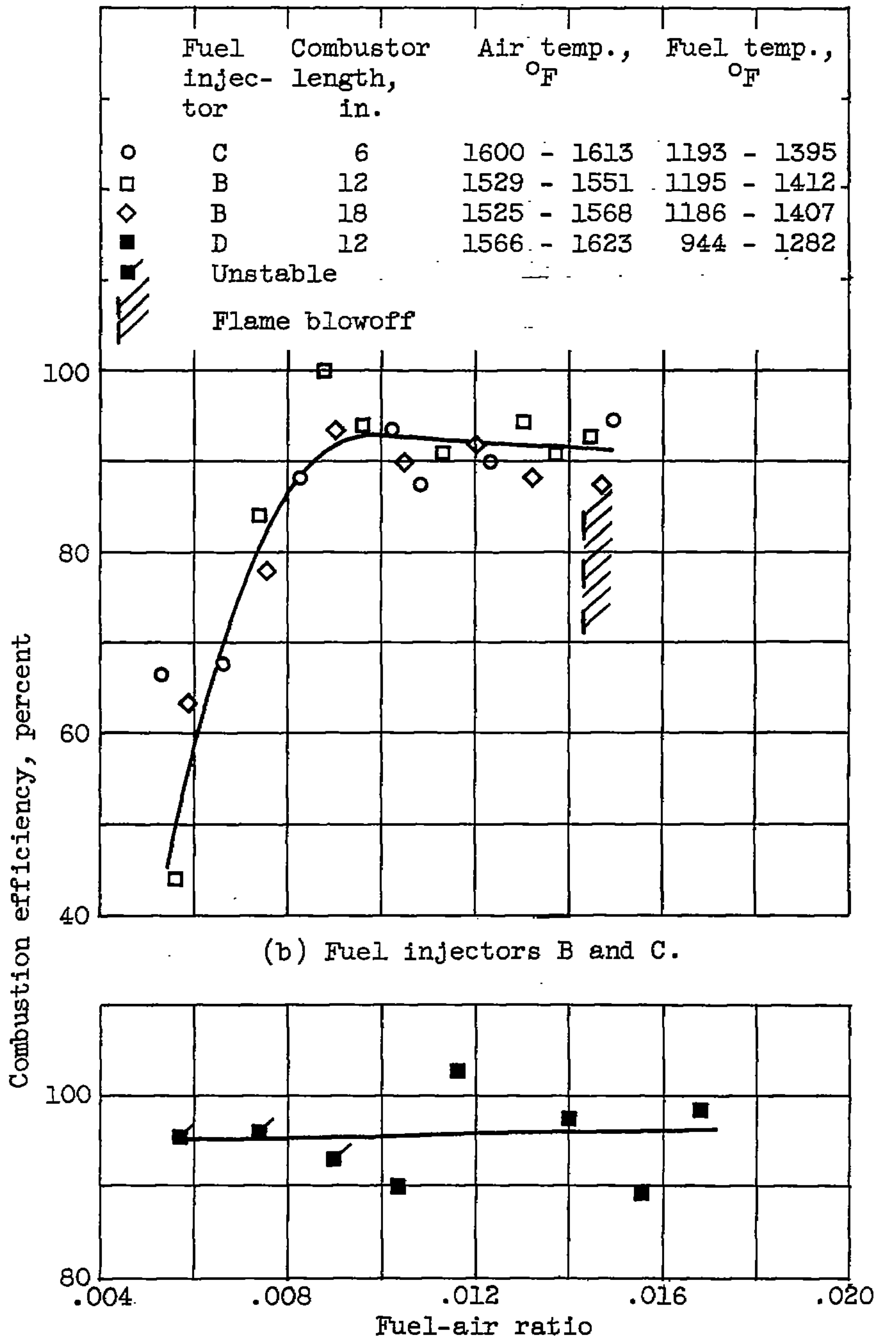


(a) Fuel injector A.

Figure 5. - Effect of fuel-air ratio on combustion efficiency of diffusion flames. Pressure, 1 atmosphere; air velocity, 115 feet per second.



(b) Fuel injectors B and C.

(c) Fuel injector D (air-cooled).

Figure 5. - Concluded. Effect of fuel-air ratio on combustion efficiency of diffusion flames. Pressure, 1 atmosphere; air velocity, 115 feet per second.

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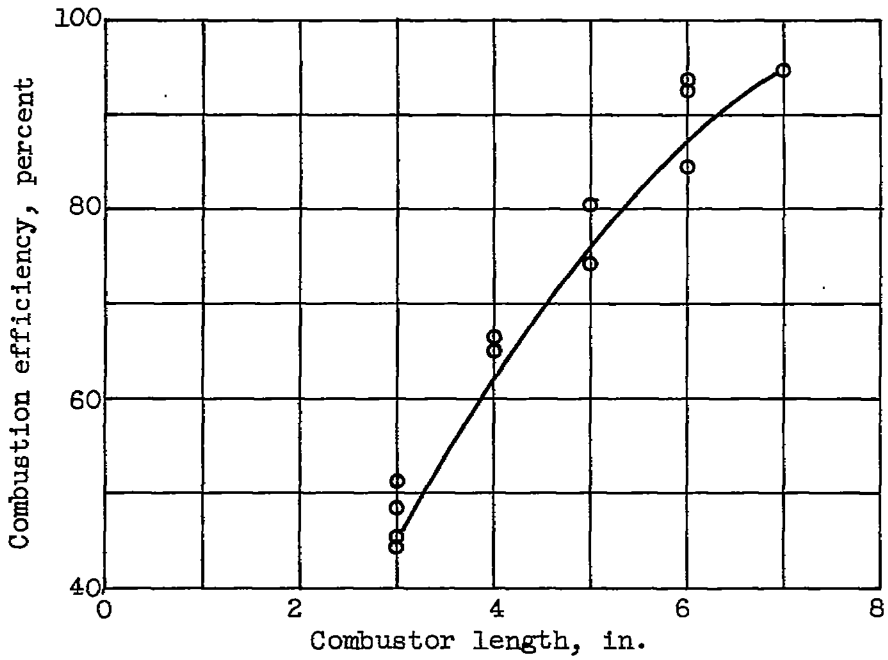

Figure 6. - Effect of combustor length on efficiency of diffusion flames with injector C. Pressure, 1 atmosphere; air velocity, 115 feet per second; fuel-air ratio, 0.011.

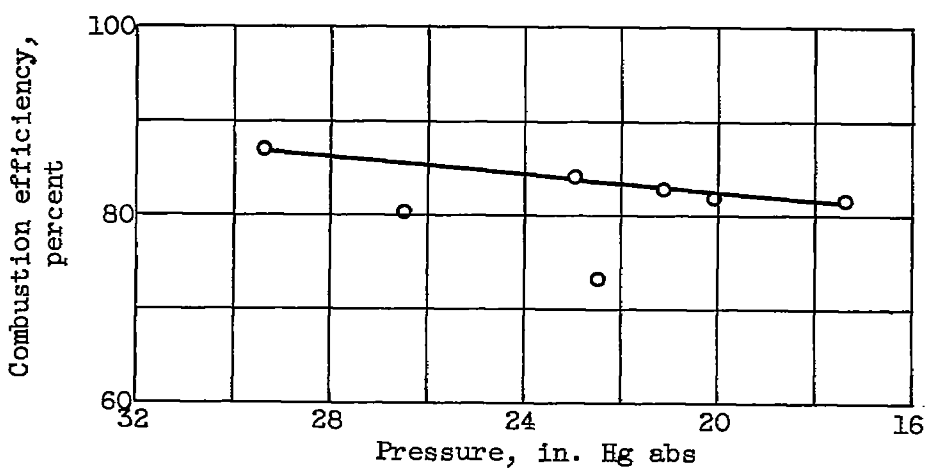

Figure 7. - Effect of pressure on combustion efficiency of diffusion flames with injector B. Air velocity, 115 feet per second; fuel-air ratio, 0.013; combustor length, 12 inches; air temperature, 1515° to 1584° F; fuel temperature, 1221° to 1380° F.

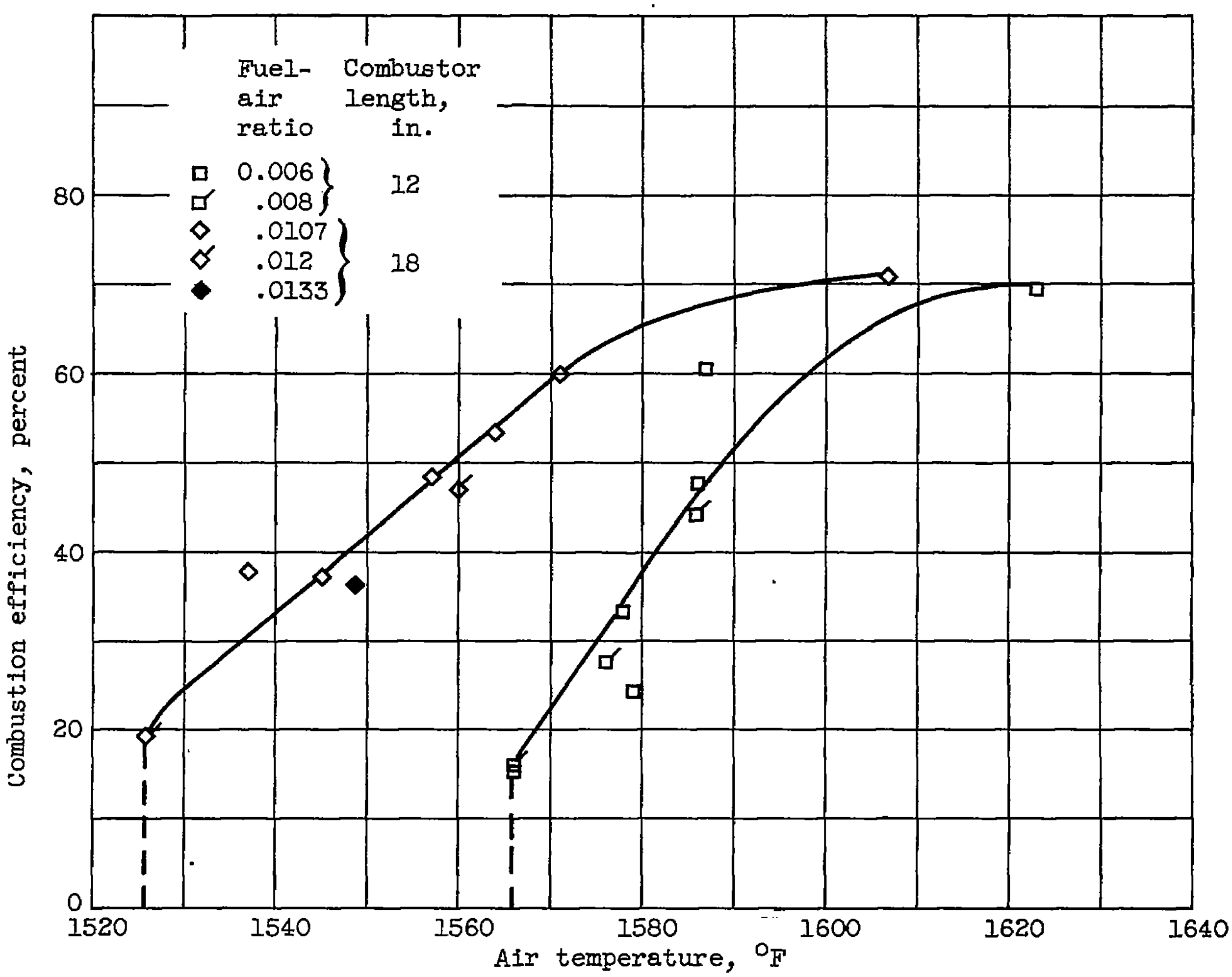

Figure 8. - Effect of air temperature on combustion efficiency of ignition-stabilized flames with fuel injector D (air-cooled). Pressure, 1 atmosphere; air velocity, 114 feet per second.

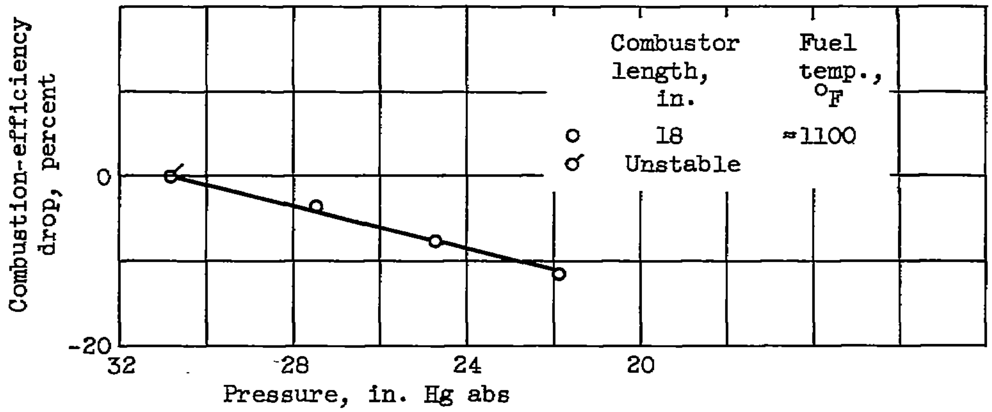

Figure 9. - Effect of pressure on combustion efficiency of ignition-stabilized flames with fuel-injector D (air-cooled). Air velocity, 114 feet per second; fuel-air ratio, ≈0.011.

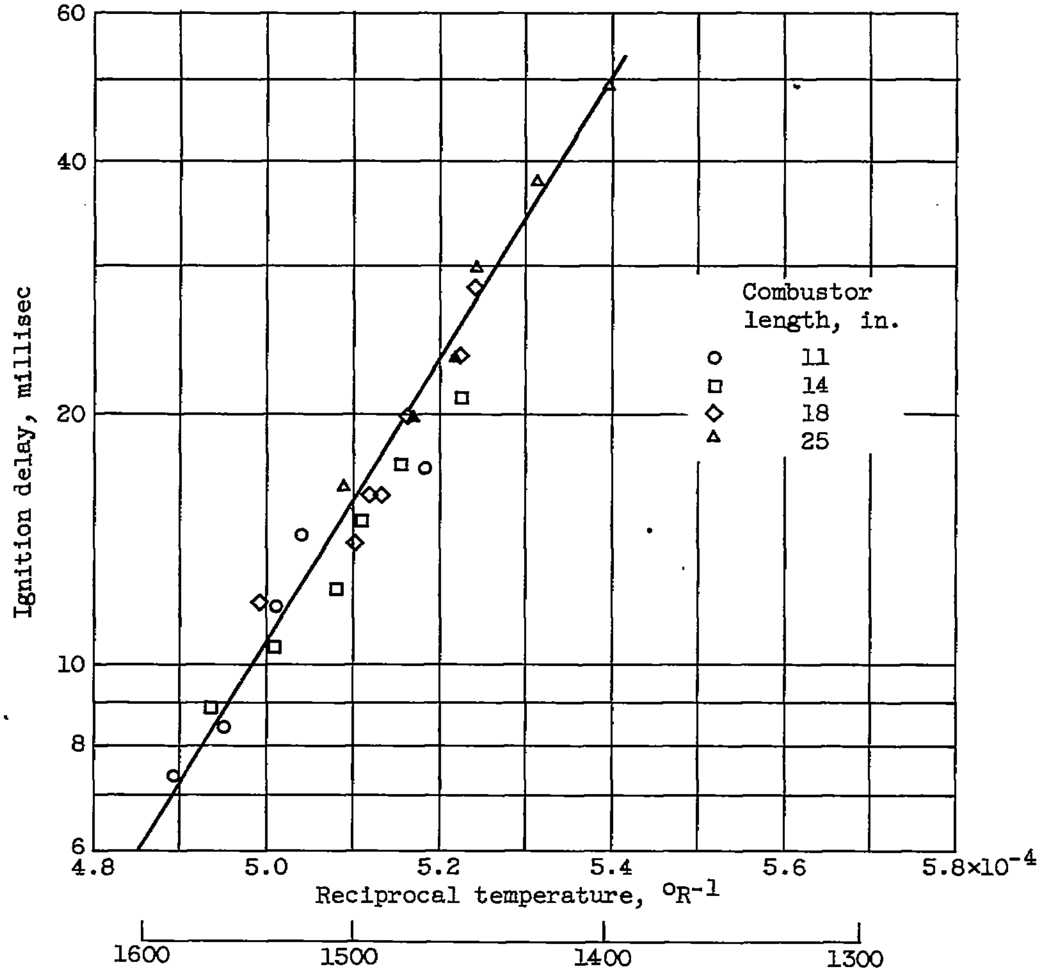

Figure 10. - Arrhenius relation for ignition delays of propane-air mixtures.